Briquetting characteristics of bean straw-maize cob blend

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Abstract

Bean straw briquettes exhibited high quality in terms of density, impact resistance and compressive strength. The impact resistance was above 96% for a particle size up to 4mm and pressures as low as 100MPa at a compacting temperature of 80°C. Reducing the compacting temperature required higher pressure and smaller particles to obtain similar quality briquettes. There were strong interactions between briquetting parameters with interaction pressure × temperature significantly affecting both density, impact resistance and compressive strength. Adding bean straw significantly improved the mechanical properties of maize cob briquettes produced at low pressure and from larger particle size. From a practical and energy point of view, a temperature of 80°C should be used for briquetting to reduce energy inputs (pressure and grinding) as this low temperature could be obtained directly from industrial waste heat.

Keywords: Briquette, density, impact resistance, compressive strength, agricultural residues

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1 Introduction

Densification of biomass into briquettes/pellets increases energy density, minimises particulate emissions per unit volume of fuel transported (increases bulk density of fuel) and improves biomass combustion efficiency (uniformity in combustion due to less dust) as well as conveyance efficiencies (less dust and wastage) in commercial energy generation facilities [1-3]. The classification of briquettes and pellets is commonly based on their size i.e. 4.0-10.0 mm diameter and 20-50mm length according to the respective Austrian (ONORM M 7135) and German (DIN 51731) quality standards for wood pellets with 10 - 200 mm diameter and 16 - 400 mm length commonly used for briquettes [4-6].

Properties of briquettes such as ash content, heating value and physical and mechanical properties (i.e. density, durability/impact resistance and compressive strength) directly relate to combustion, transport, handling and storage characteristics. Ash content and heating value are feedstock dependent. However, mechanical properties depend on briquetting conditions (feedstock moisture, particle size, compacting temperature and pressure). With respect to transport, handling and storage, briquettes with high density and mechanical strength are desirable [4, 7, 8]. Compressive strength, i.e. $\geq$ 2.56 MPa [9] is preferred during transportation and storage [10] while a high durability of over 80 % [11] is required to ensure briquettes/pellets remain intact and reduce the amount of fine particles/dust produced.

Several feedstocks have shown different responses to variation in briquetting variables [4, 12, 13, 7, 14, 15, 16]. The difference in densification characteristics of biomass materials is likely due to variation in their chemical composition which affects their binding properties. Extractives act as lubricants during compression and they prevent strong bond formation by creating a layer between particles [17], whereas lignin improves densification properties due to its thermoplastic behaviour [18]. Meanwhile, the hydroxyl group in hemicellulose and lignin helps in particle bonding through formation of hydrogen bonds [19].

Different biomass materials can be blended to enhance the mechanical properties and the combustion characteristics of briquettes due to changes in the chemical composition. The density of rice husk briquettes was increased from 415.44 - 438.02 kgm^{-3} by adding 0-5% by weight of rice bran [2]. The addition of paper mill waste (up to 30% by weight) to lignite waste improved impact resistance and compressive strength of briquettes [8].

Maize and bean are commonly cultivated crops globally thereby generating large volumes of residues. Highly durable maize cob briquettes (over 95% durability) were produced at high (200 MPa) compacting pressure [20] which could increase the costs and energy requirement for densification. However, no information is available on the densification characteristics of bean straw or a combination of bean straw with maize cob. It is expected that blending maize cob with bean straw could improve maize cob briquetting characteristics at low compacting pressure. This study focussed on analysing the impact of briquetting parameters such as pressure, temperature and particle size and their interactions on the properties of bean straw briquettes. Furthermore, the effects of blending maize cob with bean straw at different ratios on the properties of briquettes were investigated.

2 Materials and Methods

2.1 Materials

Bean straw (10.63±0.88% moisture content) was obtained from Nafferton Farm a research/commercial farm owned and managed by Newcastle University. It was part of an organic crop rotation which was left as residue in the field to dry before being collected and stored under cool/dry conditions prior to use. Maize cobs were kindly provided by Barfoots of Botley Ltd, UK. Maize (supersweet varieties) was harvested at stage R3 (milk stage) across a range of countries (EU and beyond) and stored at 0-5^{o}C for 1-25 days. The maize cobs were a mixture of varieties and are therefore representative of an agricultural processing residue. After the kernels were removed, residual cobs were sent to Newcastle University and stored in a cold room at 6^{o}C prior to briquetting. Residue maize cobs were cut into pieces <5 mm and oven dried at 105^{o}C to a moisture content of 8.62±0.20%. All moisture contents presented in this paper are expressed as % of total fresh weight. Bean straw was manually cut to <2 cm length sections. Both dried maize cobs and bean straw were crushed using a HGBTWTS3 laboratory blender 8010ES and separated using 2.36 and/or 4.00 mm sieves. Table 1 shows properties of the biomass materials. The compositions of the inorganic elements in bean straw and maize cob were determined using inductively coupled plasma (ICP). About 50 mg of each biomass material (bean straw and maize cob) was boiled in Aqua Regia (3 parts hydrochloric acid to 1 part nitric acid) for 24 hr and then evaporated. The residue was brought back into solution with 2ml of concentrated nitric acid and then diluted to 50 ml with pure water and analysed using Inductively Coupled Plasma Masss Sectrometry (ICP-MS).

Table 1 here

2.2 Briquette preparation

The briquetting machine used had a hollow cylindrical mould, internal diameter of 2 cm and length 12.5 cm as described by [20]. Briquettes were made from bean straw and a bean straw-maize cob blend.

(a) Bean straw

The impact of briquetting parameters: temperature (20-80^{o}C), particle size (<2.36 mm and <4.00 mm i.e. the sieve sizes which were available) and pressure (100, 150, 200, 250MPa i.e. within the range of pressures used for briquetting several biomass materials [21, 22]) and their interactions on density, impact resistance and compressive strength of bean straw briquettes were studied using a 2 level factorial experimental design, considering 3 replicates of the corner points and a midpoint (Table 2). The maximum compacting temperature (80^{o}C) used in this study was near the glass transition temperature of maize cob (80^{o}C) and bean straw (70^{o}C) because compacting around glass transition temperature aids plastic deformation which is essential in the formation of permanent bonds between particles [23]

Table 2 here

(b) Maize cob-bean straw blend

Briquetting of bean straw-maize cob blend was conducted after the analysis of bean straw briquetting characteristics. Pre-determined quantities of crushed bean straw and maize cob (both of particle size <4.00 mm) were mixed in the ratios of 100:0, 75:25, 50:50, 25:75 and 0:100 bean straw:maize cob on a weight basis; stirred to obtain a uniform mixture and immediately briquetted. The effect of bean straw:maize cob blend on briquetting properties was assessed. Bean straw-maize cob mixtures were compressed at compacting pressure/temperature of 200MPa/80^{o}C (i.e. the optimal pressure/temperature identified for both bean straw and maize cob) or 150MPa/50^{o}C (i.e. to assess the possibility of minimising the energy requirement) and a particle size of <4.00mm which was optimal for both maize cob [20] and bean straw.

About 7g of ground bean straw or bean straw-maize cob mixture at the desired composition as described above was fed inside the mould and manually compressed using a 10 tonne Hydraulic Bench Press (Clarke CSA10BB). A dwell time (i.e. duration for which particles under compression remain under maximum/required compacting pressure during briquetting) of 20s was chosen for all experiments to minimise briquette relaxation [7, 24] that may have negative impacts on briquette properties. Briquettes were stored in an air tight container at room temperature (approximately 20^{o}C) for 7 days to allow stabilisation [25] prior to analysis of their properties (density, impact resistance and compressive strength).

2.5 Briquette characterisation

Moisture, ash, volatile matter and fixed carbon content of bean straw and maize cob-bean straw briquettes were determined according to BS 1016-6 standard. Ultimate analysis was carried out using an elementar vario macro cube to determine percentage of carbon and nitrogen. High heating value (HHV) was determined using a CAL2K ECO bomb calorimeter. Scanning electron microscopy (SEM) analysis was carried out using a TM3030 Hitachi Microscope. Differential Scanning Calorimetry (DSC) analysis was carried out (DSC Q20 model) to identify glass transition temperature to determine the range of compacting temperatures to be used in the briquetting experiments. Analysis of neutral detergent fibre (NDF) was carried out by enzymatic gravimetry, while acid detergent lignin (ADL) and acid detergent fibre (ADF) were analysed using an Ankom 220 analyser. The composition of cellulose, hemicellulose and lignin were subsequently determined [26].

$$\text{Cellulose} = \text{Neutral detergent fiber (NDF)} - \text{Acid detergent lignin (ADL)} \quad (1)$$

$$\text{Hemicellulose} = \text{Neutral detergent fiber (NDF)} - \text{Acid detergent fiber (ADF)} \quad (2)$$

$$\text{Lignin} = \text{Acid detergent lignin (ADL)} \quad (3)$$

Density= mass/volume was determined using the stereometric method which allows briquettes being used for thermo-chemical applications to remain dry [27]. For impact resistance, a briquette was released 4 times from a height of 1.85 m to fall freely under gravity onto a metallic plate to determine impact resistance according to the method of Ndindeng et al [28]. Percentage residual weight of briquettes was determined after each drop. The remaining piece with the highest weight was taken as the residue and used for the next drop. Impact resistance was defined as the percentage residual weight after the 4th drop.

Compressive strength was determined via both the cleft and simple pressure tests using a Tinius Olsen H50KS compressing machine. Briquettes were placed between two flat parallel surfaces with surface area greater than the briquette. Briquettes were placed horizontally for the cleft test and vertically for the simple pressure test. An increasing load was then applied to compress briquettes at a rate of 1 mm min^{-1} until the briquette failed/cracked. The ultimate load at the point where the briquette cracks, F was used to calculate the compressive strength using Equations (4) and (5).

$$Compressive\ strengt, \sigma = F/A \tag{4}$$

$$Compressive\ strength, \sigma = F/l \tag{5}$$

Where A and l are the cross-sectional area (m^2) and length (m) of briquettes.

The physical and mechanical properties of briquettes such as density, impact resistance and compressive strength are presented as mean values of 6 samples/briquettes. The impact of pressure, moisture content, particle size and temperature and their interactions on density, impact resistance and compressive strength of briquettes were analysed using Minitab 17 at a significance level of α=0.05, based on the design of experiment in Table 2.

3 Results and discussion

3.1 Density of bean straw briquettes

Density is an important property that directly relates to the energy to volume ratio of briquettes [4] and is key in determining the handling, transportation (reducing logistic costs), ignition and combustion characteristics [29]. However, increasing density reduces porosity thereby reducing air circulation, hence reducing combustion rate [9]. The extent of this impact is feedstock and briquetting condition (such as pressure, temperature and particle) dependent. In this study, density of bean straw briquettes ranged between 886.0-1123.3 kg m^{-3} with variation in the briquetting parameters studied. The lowest density of 886 kgm^{-3} was produced at a low compacting temperature of 20 ^oC with a large particle size <4mm and a low pressure of 100MPa whereas the highest density (1063.0-1123.3kg m^{-3}) was produced at both tested particle sizes (<2.36 mm and <4.00mm), pressure ≥ 150MPa and high temperature (50-80^oC). All briquettes produced at low pressures (100-150 MPa) and low temperature (20 ^oC) together with those at medium pressure (200 MPa), low temperature (20 ^oC) and large particle size (<4.00 mm) had density below 1000 kg m^{-3} which falls below the range 1000-1400 kg m^{-3} as required by the German Standard DIN 51731. Irrespective of the compacting pressure and particle size, all briquettes produced at a high compacting temperature (80 ^oC) had density >1000 kg m^{-3}. Density increased with increasing temperature and pressure, though, it was maximised at particle size of <3.18mm (Fig 1a). Although particle size had a small effect, temperature and pressure were the predominant factors affecting density which agreed well with findings on tropical hardwood sawdust briquettes using a pressure range of 10-50 MPa [13]. However, Rhén et al [15] reported that under compacting pressure of 46-114 MPa, density of spruce pellets was predominantly affected by temperature (26-144 ^{o}C) and moisture (6.3-14.7 %). Increasing temperature above 50^{o}C had little effect on density (Fig 1a), indicating that briquetting temperature of 50-80 ^{o}C could be used to produce high density briquettes.

All briquetting variables and their interactions had significant impact ($P<0.05$) on density (Fig 2a; Table 3) except for the particle size x temperature interaction. Particle size had a significant impact only at low compacting temperature (20 ^{o}C) and compacting pressure of 100-200 MPa, where density decreased with an increase in particle size (Fig 3a), most likely due to high resistance to plastic deformation of particles at this temperature and range of pressure. Therefore, high pressure (250 MPa) is required to crush and bind large particles (<4.00mm) together, producing equally high-density briquettes as particles size <2.36mm. At low compacting temperature (20 ^{o}C), density increased with increasing compacting pressure (100-250MPa) (Fig 3a). This trend is consistent with results reported in the literature for briquettes from waste paper and wheat straw [4], palm kernel cake pellet [30], beech sawdust [21] and neem powder and sawdust [31]. The increasing trend in density with increasing compacting temperature (Fig 3a) within the range of temperatures used (20-80 ^{o}C) agrees well with findings on pellets produced from several biomass feedstocks e.g. spruce, birch, reed canary grass (room temperature to 80 ^{o}C) [17] wheat straw and wheat straw extract pellets (30-100 ^{o}C) [32]. Furthermore, Razuan et al [30] also reported an increasing trend in density of palm kernel cake pellets (average particle size 2 mm and moisture 7.9%) as temperature was increased from 20 to 100 ^{o}C, however, further increasing temperature above 100 ^{o}C, reduced the density and compressive strength. Similarly, Gilbert et al [33] obtained highest density and strength of switchgrass pellets at 100 ^{o}C in an operating temperature range of 14-125 ^{o}C.

Table 3 here

Fig 1 here

Fig 2 here

3.2 Impact resistance of bean straw briquettes

Impact resistance is a measure of durability of briquettes which defines the tendency of a briquette to produce dust or break when it is subjected to a destructive force. It is an indicator of mechanical strength [34] where briquettes with high impact resistance/durability are desirable to minimise breakage and dust formation during transport and conveying. Impact resistance of >80% is required for handling and transportation efficiency [34, 35]. In this study, the impact resistance of bean straw briquettes was well above 80% (up to 99.8% in some cases), except for briquettes derived from a low compacting pressure of 100MPa, with small particles (<2.36mm) and at a low temperature (20 ^{o}C) (Fig 3b). These briquettes lost more than 20% of their weight and therefore are less resistant to the destructive forces experienced during transport and handling. The large amount of fine particles and dust (>20%) generated could potentially cause disturbance to boiler feed systems, lead to reduced efficiency of combustion and increase the risks of fire and explosion during transport, handling and storage [36]. All bean straw briquettes produced at high temperature (80 ^{o}C) and high compacting pressure (200-250MPa) had high impact resistance with <2.5 % dust/fine particles generated and are therefore highly durable and satisfy European Standard Committee CEN/TC335 (for solid biofuels) for durability. These highly durable briquettes (impact resistance >97.5%) would also help minimise health related problems resulting from fine particles/dust [37].

For bean straw, temperature and pressure were found to be the predominant factors (Fig 1b) affecting impact resistance whereas particle size in the range tested had little effect. Increasing pressure and temperature from 175-250MPa and 50-80^{o}C respectively had little impact (Fig 1b). However, according to Castellano et al., [18], increasing particle size from 2mm to 4mm decreased the durability of pine, oat, triticale and rice straw briquettes but had no influence on that of *Eucalyptus camaldulensis* and Pyrenean oak briquettes. Similarly, under compacting pressures of 1.5MPa [3], increasing particle size from <1.41mm to 1.41-3.17mm significantly decreased the durability of larch pellets but had no impact on the durability of tulipwood pellets. The authors found that increasing compacting temperature (120-180 ^{o}C) significantly increased the durability of pellets from both feedstocks. From previous studies [20], impact resistance of maize cob briquettes at a moisture content range of 7-17% was significantly reduced by increasing particle size from <2.36-<4mm. From all of the aforementioned studies, it can be concluded that the effect of particle size is feedstock dependent.

There was a significant (P< 0.05) pressure x temperature interaction on impact resistance (Fig 2b; Table 4). At low compacting temperature (20 ^{o}C), impact resistance increased with increasing pressure from 100-200 MPa and remained constant with further increments to 250 MPa (Fig 3b). This indicates that maximum inter-particle bonding was achieved at compacting pressure ranging between 200-250MPa at 20^{o}C. Rajaseenivasan et al [31] also observed an increasing trend in impact resistance of neem powder and sawdust briquettes when pressure was increased from 7 to 33 MPa. Increasing compacting temperature (20-80 ^{o}C) significantly increased impact resistance (Fig 3.b) at low compacting pressures (100-150MPa) and at 80 ^{o}C. At the high temperature of 80^{o}C, impact resistance was independent of compacting pressure and particle size.

Table 4 here

Fig 3 here

3.3 Compressive strength of bean straw briquettes

Compressive strength is the maximum load that a briquette can withstand before it breaks. It is used to estimate the compressive stress resulting from the weight of the top briquettes on lower briquettes during storage, transport and handling [38]. It is also a measure of mechanical strength, therefore the higher the value the better. In this study, compressive strength was measured by both the in cleft and simple pressure tests. This study revealed a strong positive correlation between compressive strength in cleft and simple pressure (data not shown) which agreed well with previous findings [20] and therefore, only data for compressive strength in simple pressure, referred to as compressive strength (CS) hereafter, are presented. CS ranged between 69.3-99.9 MPa with variations in briquetting parameters. All briquettes had CS much higher the minimum recommended value i.e. > 2.56 MPa, [9] for efficient transport, storage and handling with minimal breakage.

Temperature and pressure were the predominant factors affecting CS (Fig 1c). It was reported [13] that pressure (10-50 MPa) was the predominant factor affecting CS of tropical hardwood sawdust briquettes (i.e. *C. pentandra*, *T. scleroxylon*, *A. robusta*, *T. superba*, *P. Africana*, and *C. mildbreadii*) made from particles <3.35 mm with a moisture content of 11.46%. Moisture

(6.3-14.7 %) and temperature (26-144 ^{o}C) predominantly affected CS of spruce pellets under compacting pressures 46-114 MPa [15]. While moisture content (between 2 and 14 %) was the predominant factor affecting CS of birch, spruce and reed canary grass pellets produced from compacting pressures of 200-400MPa and a particle size of <1.00mm [17]. Such variations can be attributed to variations in feedstock properties and briquetting parameters used in the different studies.

Compressive strength increased with increasing pressure and temperature whereas it decreased significantly (P<0.05) with increasing particle size (Fig 1c and Table 5). Mechanical strength and density depend on the strength of inter-particle bonds which are affected by particle size, compacting pressure and temperature. Small particles have large surface areas thereby helping to form strong bonds (with and without solid bridges) between particles during briquetting [39]. In bonding without solid bridges, solid particles are attracted to each other by actions of short-range forces such as molecular (van der Waal's forces, hydrogen bridge and valence force i.e. free chemical bond) and electrostatic forces. Valence and Van der Waals' forces can contribute to bonding when seperation between particles are about 10 Å and 0.1µm respectively [40, 20]. Bonding by action of electrostatic force occurs due to the presence of excess charge which may by created from grinding and inter-particle friction [40]. Therefore, the forces contributing to bonding become less effective for large pore sizes, thereby weakening the briquettes. During bonding by solid brigde formation application of high pressure and temperature cause diffusion of molucules from one particle to another. Solid brigdes can also be formed as a result of chemical reactions and solification of melted components [40, 41]. These observations are in agreement with studies on maize cob under particle size (<2.36-<4.00 mm) with compacting pressure of 150-250MPa [20] and pine with particle size of 0.5-4.0 mm and pressure of 31-318 MPa [42]. However, it contradicts Zhang and Guo   [43] where for varying caragana korshinskii kom particle sizes (0.16-5.0 mm), minimum briquette CS (62.16 MPa) was obtained at a particle size <0.16 mm under a compacting pressure and temperature of 10-170 MPa and 70-150 ^{o}C. These differences in results confirm the need to analyse variations in briquettes properties on an individual feedstock basis.

Pressure x temperature and pressure x particle size x temperature interactions significantly affected compressive strength (P<0.05, Fig 2c; Table 5). Irrespective of the compacting temperature, compressive strength increased with increasing pressure (100-150MPa) but remained relatively constant with further increments in pressure up to 250 MPa. Increasing pressure squeezes natural binder components out of biomass particles and also causes plastic and elastic deformation of particles thereby reducing void spaces between particles and increasing inter-particle bonding by solid bridge formation, increasing contact areas (which increase short range forces such as molecular and electrostatic forces) and through mechanical interlocking, consequently increasing both density and strength [13, 44, 43, 14].

Compressive strength increased with increasing temperature for the tested range of compacting pressures (Fig 3c). The highest, increment of 27% was observed at low pressure i.e. 100 MPa and particle size <2.36 mm when temperature was increased from 20-80 ^{o}C, most likely due to high particle resistance to deformation at low pressure (100 MPa) and temperature (20 ^{o}C). Temperature minimises relaxation and improves the degree of densification by: (i) softening biomass particles, consequently aiding plastic deformation upon compression and increasing the inter-particle bonding through mechanical interlocking and (ii) facilitating the release of natural binders such as lignin, cellulose and hemicellulose which form solid bridges upon cooling thereby increasing the mechanical strength and density [33, 41]. Natural binders such as lignin and hemicellulose can undergo plastic deformation or be squeezed out of particles during compression at temperatures near the glass transition tempearture [23] which was 70 ^{o}C in this study. Increasing temperature (from 20-80 ^{o}C) not only improved briquette density and mechanical strength but also reduced the briquetting pressure required, which can potentially reduce production costs by directly minimising the energy required for compression. The use of high pressure is associated with high electrical energy consumption and high wear and tear of briquetting equipment [45]. Heat softens biomass particles, reduces friction between particles and the mould, thereby minimising costs of depreciation, repair and maintenance resulting from wear and tear [45].

The increasing trend in compressive strength with increasing pressure or temperature agreed well with trends reported for palm oil mill residue briquettes (pressure 3-11MPa) [9], torrefied switchgrass [33] and hazelnut shell charcoal (particle size of >2.0 mm, pressure of 800 MPa, using 6.5-18.0 %wt pyrolysis oil as a binder) [46].

Table 5 here

3.4 Bean straw-maize cob blended briquettes

Density, impact resistance and compressive strength of bean straw-maize cob mix briquettes ranged between 949.3-1154.2 kgm^{-3}, 63.2-99.8%, and 30.5-99.6 MPa respectively with variations in the bean straw:maize cob blend ratio of 0:100% by weight. All briquettes satisfied the German Standard DIN 51731 with density 1000-1400 kgm^{-3} except for bean straw:maize cob blend ratio of 0:100 under a low compacting pressure of 150 MPa and a temperature of 50 ^{o}C which produced briquettes with the lowest density i.e. 949.3 kgm^{-3}. These briquettes also had the lowest impact resistance (63.2%) which did not attain the minimum recommended value of 80%. However, all other briquettes had both impact resistance and compressive strength above the minimum values of 80% and 2.36 MPa required to minimise breakage and dust formation.

Blend ratio had no effect on impact resistance at high pressure and temperature of 200MPa/80^{o}C (Table 6). However, at a low compacting pressure/temperature of 150MPa/50^{o}C, impact resistance was reduced by ~36% as maize cob content increased from 75-100%. Although increasing maize cob content from 0-75% reduced density by <5%, CS decreased by 47-49% (Table 6). This is most likely due to higher resistance of maize cobs to plastic deformation. From scanning electron microscopy (SEM) imaging (Fig 4), maize cob is highly porous compared to bean straw which could have increased resistance to plastic deformation thereby increasing the energy requirement (high pressure) to minimise separation between and within (pores) particles. During briquetting, pressure causes particles to first rearrange to form closely packed mass and secondly to elastically and plastically deform when pressure increases. During plastic and elastic deformation, particles move and fill void spaces which increases contact area, consequently increasing both density and strength [44, 14]. Lastly, volume is significantly reduced, resulting in the density of the material approaching the true density of the component ingredients. By the end of this stage, the deformed/broken particles cannot change position because of a decreased number of cavities [44]. Sole bean straw and a bean straw:maize cob blend ratio of 75:25 by weight were the best substrates for producing briquettes with high density and mechanical strength (Table 6). Blending improved both the density and mechanical strength of maize cob briquettes but these properties were lower when compared with bean straw only briquettes. The optimal bean straw:maize cob blend ratio was 75:25 producing equally high density briquettes as sole bean straw.

Scanning electron microscopy (SEM) images (Fig 4) of briquettes which were broken from the middle in a direction perpendicular to the axis of the cylindrical briquettes shows that bonding in bean straw is strongly enhanced by mechanical interlocking while for maize cobs bonding was mainly by solid bridge formation. Application of high pressure and/or temperature during densification results in diffusion of molecules at the point of contact from one particle to another, thus forming solid bridges while fibrous or bulky particles interlock to form mechanical interlocking bonds [41]. Particles of corn stover and switchgrass briquettes/pellets are bonded mainly by solid brigdes resulting from natural binders i.e. mainly lignin and protein [40]. Variations in the bonding mechanism are likely to be due to differences in the nature of biomass materials and in particular the more fibrous nature of the bean straw. During compression, interlocking bonds are formed [41] with increasing strength and density. As the proportion of maize cob content was increased, the extent of bond formation by mechanical interlocking was reduced (Fig 4), most likely due to maize cob particles only filling the void spaces between the fibrous bean straw particles. The reduction in the extent of bonding by mechanical interlocking could explain the reduced strength and density of bean straw briquettes with increasing content of maize cob in the blend. In addition, variations in lignin content (maize cob 1.5% and bean straw 10.2% (Table 1)) coud have also caused a difference in densification characteristics of these materials since high lignin content provides better densification properties [1]. Maize cob has lower lignin content than bean straw therefore, increasing maize cob composition would lower the lignin content of the blend thereby reducing density and strength of resulting briquettes. A decreasing trend in density of briquettes was observed by increasing corn stover content from 0-100% in corn stover:peanut shell blends [47]. Increasing palm kernel shell content from 0-10% reduced sawdust briquette density from 420 to 380 kg m^{-3} and durability from 64.74 to 32.28%. However, further increasing palm kernel content to 50% increased density and durability to 480kg m^{-3} and 73.40% respectively [48]. Blending bamboo with rice straw in the ratio of 5:0-0:5 by weight (i.e. bamboo : rice straw) reduced density of sole bamboo (1250 kgm^{-3}) and sole rice straw (1350 kgm^{-3}) pellets (to around 1000-1100kg m^{-3}), however, durability was maximised (99.03%) with a blend ratio of 2:3 [49].

Bean straw ash content was about double that of maize cob (Table 1). Inorganic elements determine formation of deposits, fly ash emissions and ash melting point during combustion [50]. Potassium (K), sodium (Na), silicon (Si) and aluminium (Al) decrease the ash melting point while calcium (Ca) and magnesium (Mg) increase the ash melting point. Furthermore, increasing K content increases aerosol formation during combustion and hence fouling inside boilers and increased particulate emissions [51, 50]. Variations in the effect of the inorganics elements on ash melting point are likely due to variation in their melting temperatures. Generally, the composition of the inorganic elements was higher in bean straw than in maize cob (Table 1). This demonstrates the variability in biomass properties which may indicate requirement for varying optimal conditions for processing different biomass materials for energy. Ca, K, Na, and Mg were the dominant inorganic elements in bean straw while K, Mg, Ca and phosphorous (P) were the dominant inorganic elements in maize cob. Mullen et al [26] also reported that the inorganic fraction of maize cob was predominantly K which in this study was is over 3 times the concentrations of Ca and Mg combined which is likely to lower the ash melting point of maize cob. While the high Ca concentration in bean straw is likely to increase the ash melting point of bean straw. The K concentration is high in both bean straw and maize cob which may increase aerosol formation during combustion and hence fouling inside the boiler and increased particulate emissions [51]. However, the content of the alkali metal (K and Na) may be reduced by leaching these biomass materials with water [50]. The content of heavy metals such as As, Cr, Cu, Pb and Zn were determined as a requirement by the German standard DIN 51731. The concentrations of heavy metals in both maize cob and bean straw were within the acceptable limits by the German standard DIN 51731 i.e. As <0.8mg/kg, Cr < 8mg/kg, Cu < 5mg/kg, Pb < 100mg/kg and Zn < 100mg/kg. Heavy metal content is required to be as low as possible as it affects ash quality and particle emissions [51]. Therefore, fuel ash content has to be minimised for process efficiency [51]. In this study, increasing maize cob content in the blend: (i) increased briquette volatile composition due to higher volatile content in maize cobs compared to bean straw and (ii) reduced ash and fixed carbon content (Table 7). Blending had a higher impact on ash content than on volatile and fixed carbon contents. Increasing maize cob content from 25-50% did not result in a significant change in HHV (17-17.9 MJ kg^{-1}), fixed carbon and volatile contents. The high heating values (HHV) of the bean straw-maize cob blend in the current study are comparable with that of switchgrass (17.3 MJ kg^{-1}) [33], peanut shells (17.55 MJ kg^{-1}) and coconut fiber (17.74 MJ kg^{-1}), but higher than those of sawdust (14.99 MJ kg^{-1}), rice husk (14.77 MJ kg^{-1}) and palm fibre (16.84 MJ kg^{-1}) [24] which means from the same amount of fuel, more energy can be generated from the blend.

Table 6 here

Table 7 here

Fig 4 here

4 Conclusions

This study revealed that increasing pressure and temperature improved bean straw briquette density and mechanical strength. However, particle size had little impact at compacting pressure/temperature of 250MPa/20^{o}C and at compacting temperature of 80^{o}C irrespective of compacting pressure tested. All bean straw briquettes at pressure 100-200MPa and temperature of 80^{o}C satisfied the German Standard DIN 51731 (density 1000-1400 kg m^{-3}). Strong interactions were observed between briquetting parameters with interaction pressure × temperature significantly affecting density, impact resistance and compressive strength. Blending of bean staw:maize cob enhanced briquette characteristics with an optimum 75:25 (wt:wt) ratio producing equally high density briquettes similar to sole bean straw. However, sole bean straw produced briquettes with highest density and mechanical strength with a lower energy expenditure (pressure and /temperature) and therefore is a preferred substrate over maize cob for briquette production.

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Figure captions

Fig 1: Effects of briquetting parameters: pressure, particle size and temperature on (a) density, (b) impact resistance and (c) compressive strength (CS) of bean straw briquette. Red square represents the mid-point.

Fig 2: Interaction effects of briquetting parameters: pressure, moisture content, particle size and temperature on (a) density, (b) impact resistance and (c) compressive strength (CS) of bean straw briquette. Red square represents the mid-point.

Fig 3: Effect of compacting conditions (temperature, pressure) and feedstock particle size (legend: particle size (mm)/ compacting temperature (^{o}C)) on briquette (a) density, (b) impact resistance and (c) compressive strength of bean straw briquette

Fig 4: Bonding in bean straw:maize cob briquettes produced at compacting pressure of 200MPa with a moisture content of 10.63% for bean straw and 8.62% for maize cobs

Table 1: Properties of bean straw and maize cob

Property	Maize cob	Bean straw
Proximate properties (dry basis)		
Ash (%wt)	3.0	6.8
Volatile (%wt)	80.6	69.1
Fixed carbon (%wt)	16.4	24.1
Ultimate properties (dry and ash free)		
C (%)	46.9	43.6
N (%)	2.8	2.6
High heating value (HHV) (MJ/kg)	18.9	17.6
Cellulose (%)	17.7	21.4
Hemicellulose (%)	29.4	19.6
Lignin (%)	1.5	10.2
Extractives (%)	51.4	48.8
Inorganic composition		

B (µg/g)	7.2	102.2
Na (µg/g)	12.9	2523.8
Mg (µg/g)	778.8	1939.8
Al (µg/g)	-	9.3
P (µg/g)	351.8	68.1
K (µg/g)	3854.5	4014.6
Ca (µg/g)	375.4	18047.9
Sc (µg/g)	0.2	0.1
Ti (µg/g)	0.6	0.9
V (µg/g)	0.3	0.3
Cr (µg/g)	2.1	1.1
Mn (µg/g)	13.3	26.6
Fe (µg/g)	-	53.6
Co (µg/g)	-	0.1
Ni (µg/g)	0.6	0.6
Cu (µg/g)	19.0	46.6
Zn (µg/g)	33.7	36.3
Ga (µg/g)	0.2	4.7
As (µg/g)	0.2	-
Rb (µg/g)		
Sr (µg/g)	1.2	49.5
Mo (µg/g)	0.2	-
Sn (µg/g)	0.4	0.5
Ba (µg/g)	2.8	91.6
Ce (µg/g)	-	0.1
Pb (µg/g)	2.2	2.1

Table 2: Design of experiment for statistical analysis of the effects of pressure (MPa), particle size (mm) and temperature (^{o}C) on properties of briquette. Midpoint: pressure/particle size/temperature of 175/3.18/50

Pressure (MPa)	Particle size (mm)	Temperature (^{o}C)
250	2.36	80
250	2.36	80
100	2.36	80
100	4.00	80
100	4.00	20
100	2.36	80
250	4.00	20
100	2.36	20
100	4.00	80
250	4.00	80
250	4.00	80
250	2.36	20
100	2.36	20
100	2.36	20
100	4.00	20
175	3.18	50
250	4.00	20
100	2.36	80
250	4.00	20
100	4.00	80
250	2.36	20
250	2.36	80
100	4.00	20
250	4.00	80
250	2.36	20

Table 3: Analysis of variance for bean straw briquette density

	Degrees of freedom	Sum of squares	Mean sum of squares	F-value	P-value
Pressure (*p*)	1	93900	93900.1	2081.85	0.000
Particle size (*s*)	1	728	728.2	16.14	0.001
Temperature (*t*)	1	50729	50728.8	1124.70	0.000
$p \times s$	1	330	330.0	7.32	0.016
$p \times t$	1	1438	1438.4	31.89	0.000
$s \times t$	1	39	38.5	0.85	0.369
$p \times s \times t$	1	713	712.9	15.80	0.001
Error	16	722	45.1		
Total	24	149678			

Table 4: Analysis of variance for bean straw briquette impact resistance

	Degree of freedom	Sum of square	Mean sum of square	F-value	P-value
Pressure (*p*)	1	670.98	670.984	61.94	0.000
Particle size (*s*)	1	1.76	1.760	0.16	0.692
Temperature (*t*)	1	953.82	953.820	88.06	0.000
$p \times s$	1	18.55	18.550	1.71	0.209
$p \times t$	1	662.55	662.550	61.17	0.000
$s \times t$	1	1.35	1.354	0.12	0.728
$p \times s \times t$	1	9.00	9.004	0.83	0.375
Error	16	173.31	10.832		
Total	24	2512.88			

Table 5: Analysis of variance for bean straw briquette compressive strength

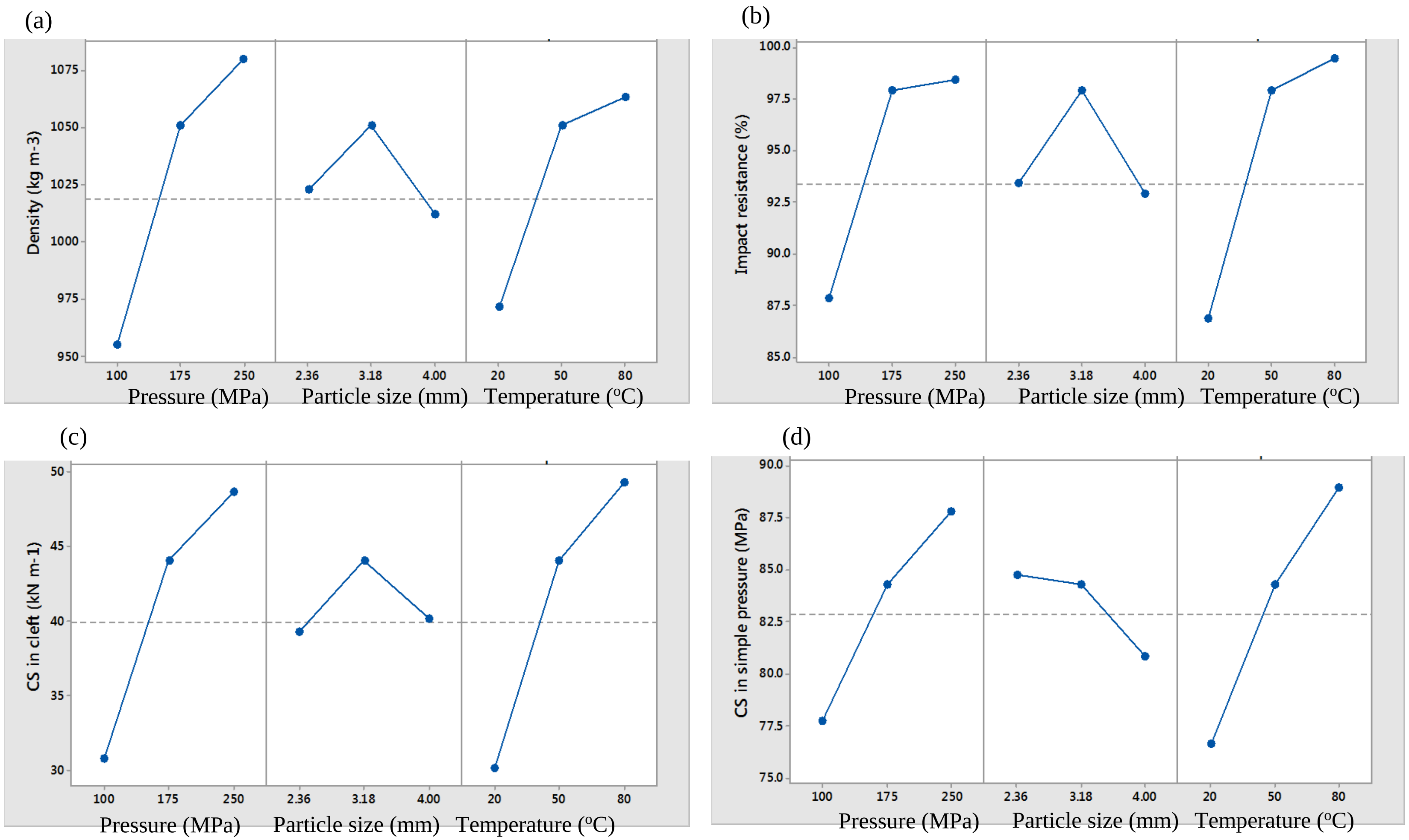
	Degree of freedom	Sum of square	Mean sum of square	F-value	P-value
Pressure (*p*)	1	606.01	606.015	47.79	0.000
Particle size (*s*)	1	92.04	92.042	7.26	0.016
Temperature (*t*)	1	907.74	907.740	71.59	0.000
$p \times s$	1	32.20	32.202	2.54	0.131
$p \times t$	1	83.63	83.627	6.60	0.021
$s \times t$	1	3.23	3.227	0.25	0.621
$p \times s \times t$	1	61.44	61.440	4.85	0.043
Error	16	202.87	12.680		
Total	24	1991.40			

Table 6: Effect of blending ratio (bean straw:maize cob) on density, impact resistance and compressive strength of briquettes

Bean straw:maize cob ratio (wt:wt)	Pressure: 200 MPa and temperature: 80 °C			Pressure: 150 MPa and temperature: 50 °C		
	Density (kg m^{-3})	Impact resistance (%)	CS (MPa)	Density (kg m^{-3})	Impact resistance (%)	CS (MPa)
100:0	1153.2	99.8	99.6	1063.0	99.8	92.6
75:25	1154.2	99.4	83.6	1052.9	99.5	69.0
50:50	1126.5	99.6	65.4	1038.1	97.7	56.5
25:75	1114.4	99.4	52.4	1019.0	98.6	47.5
0:100	1018.4	99.8	40.4	949.3	63.2	30.5

Table 7: Effect of blending ratio (bean straw:maize cob) on proximate properties of briquettes and HHV

Bean straw:maize cob ratio (wt:wt)	Ash (%)	Volatile (%)	Fixed carbon (%)	HHV (MJ kg^{-1})
75:25	5.4	69.3	25.3	17.0
50:50	4.5	69.6	25.9	17.9
25:75	3.0	72.9	24.1	17.3



(a)
Density (kg m-3)
1075
1050
1025
1000
975
950
100
175
250
Pressure (MPa)
2.36
3.18
4.00
Particle size (mm)
20
50
80
Temperature (°C)
(b)
Impact resistance (%)
100.0
97.5
95.0
92.5
90.0
87.5
85.0
100
175
250
Pressure (MPa)
2.36
3.18
4.00
Particle size (mm)
20
50
80
Temperature (°C)
(c)
CS in cleft (kN m-1)
50
45
40
35
30
100
175
250
Pressure (MPa)
2.36
3.18
4.00
Particle size (mm)
20
50
80
Temperature (°C)
(d)
CS in simple pressure (MPa)
90.0
87.5
85.0
82.5
80.0
77.5
75.0
100
175
250
Pressure (MPa)
2.36
3.18
4.00
Particle size (mm)
20
50
80
Temperature (°C)

Fig 1:

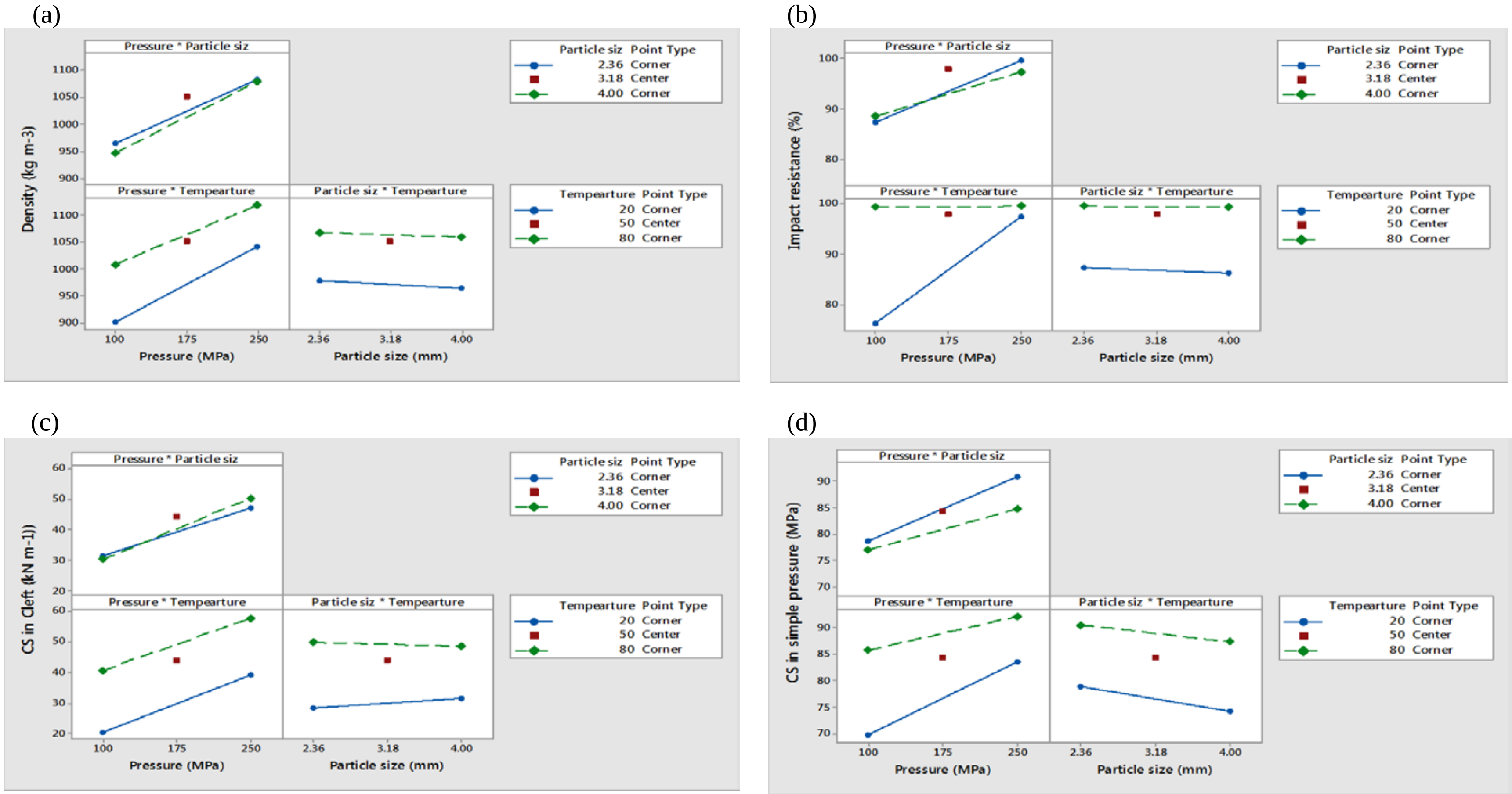

(a)
Pressure * Particle siz
Pressure * Tempearture
Particle siz * Tempearture
Density (kg m-3)
Pressure (MPa)
Particle size (mm)
Particle siz Point Type
2.36 Corner
3.18 Center
4.00 Corner
Tempearture Point Type
20 Corner
50 Center
80 Corner
(b)
Impact resistance (%)
(c)
CS in Cleft (kN m-1))
(d)
CS in simple pressure (MPa)

Fig 2:

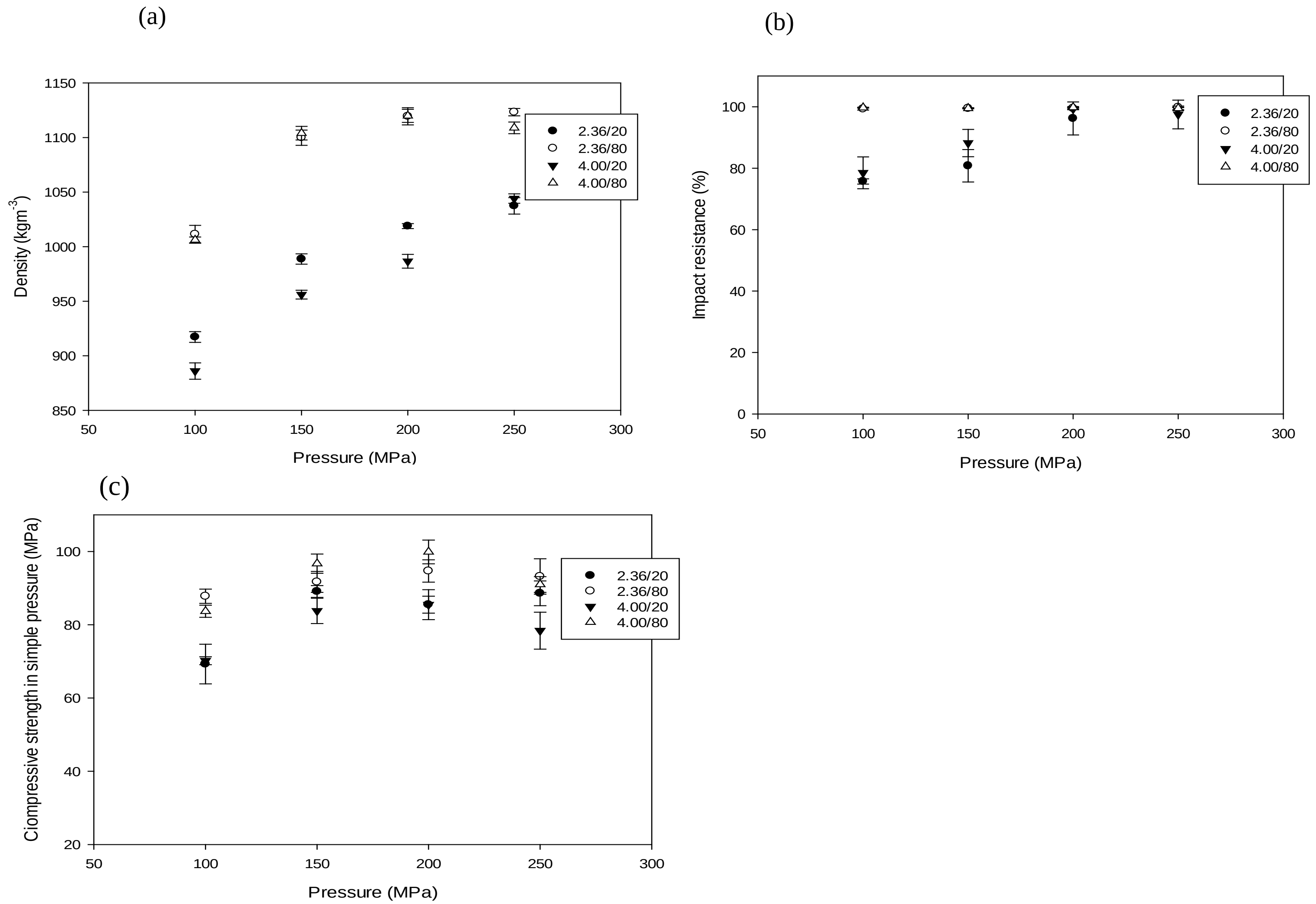

(a)
Density (kgm-3)
Pressure (MPa)
2.36/20
2.36/80
4.00/20
4.00/80
(b)
Impact resistance (%)
Pressure (MPa)
2.36/20
2.36/80
4.00/20
4.00/80
(c)
Ciompressive strength in simple pressure (MPa)
Pressure (MPa)
2.36/20
2.36/80
4.00/20
4.00/80

Fig 3:

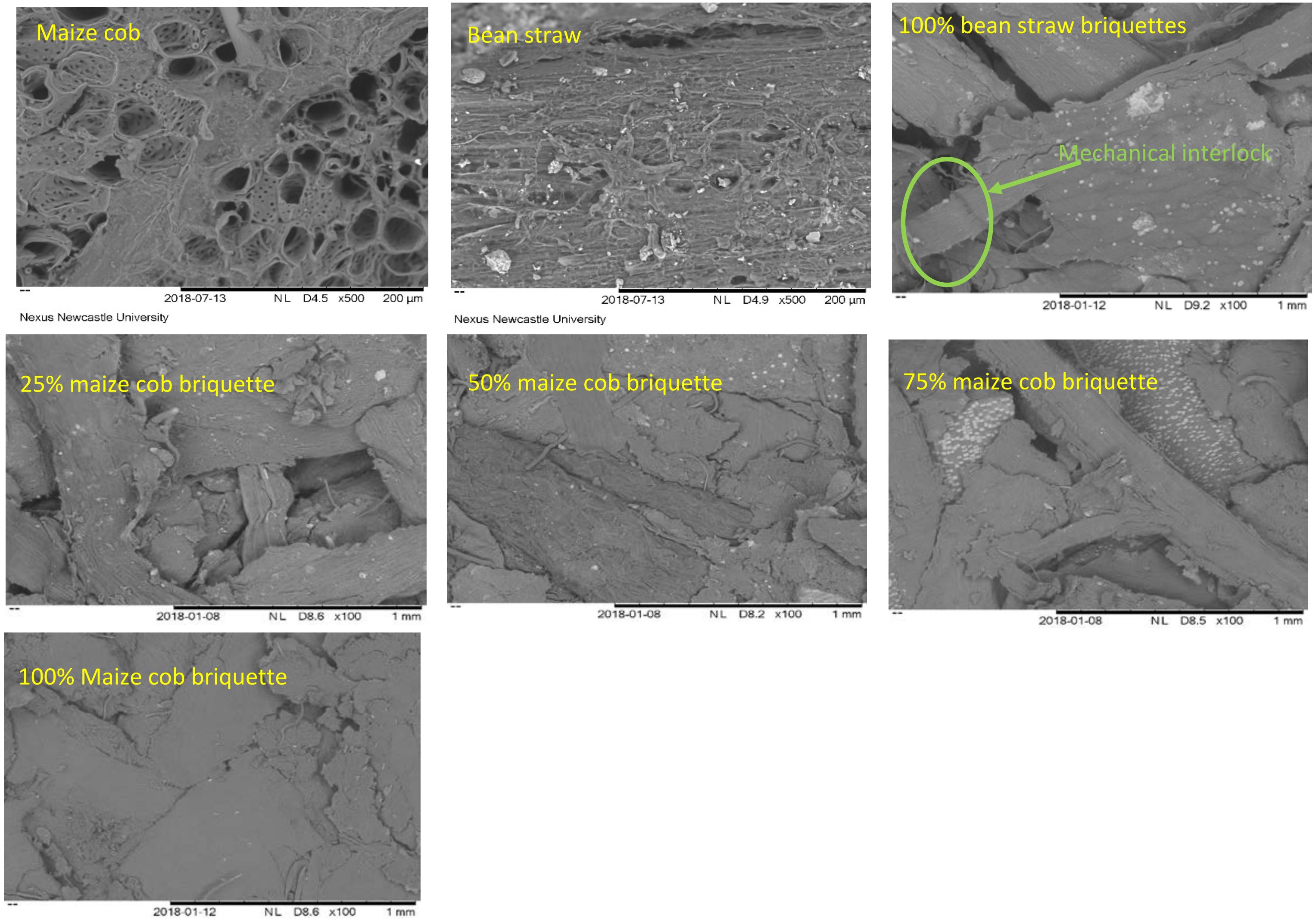

Maize cob
2018-07-13 NL D4.5 x500 200 µm
Nexus Newcastle University
Bean straw
2018-07-13 NL D4.9 x500 200 µm
Nexus Newcastle University
100% bean straw briquettes
Mechanical interlock
2018-01-12 NL D9.2 x100 1 mm
25% maize cob briquette
2018-01-08 NL D8.6 x100 1 mm
50% maize cob briquette
2018-01-08 NL D8.2 x100 1 mm
75% maize cob briquette
2018-01-08 NL D8.5 x100 1 mm
100% Maize cob briquette
2018-01-12 NL D8.6 x100 1 mm

Fig 4: